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ARGONNE CANCER RESEARCH HOSPITAL
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THE CONSEQUENCES OF INGESTION BY MAN OF REAL AND SIMULATED FALLOUT

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ABSTRACT

Real and simulated particulate fallout and solutions of $Sr^{85}Cl_2$ and $Cs^{134}Cl_2$ were fed to 102 healthy volunteers. Absorption and retention of ingested radioactivity was measured by whole body counting using the gamma-ray spectrometer at the Argonne Cancer Research Hospital. An average of 3 per cent of the radioactivity of week-old local fallout was absorbed: the range was 0 to 9 per cent. Strontium and cesium leached or dissolved from simulated fallout behaved in the same way, metabolically, after absorption as they did when the tracer was swallowed in a solution or injected intravenously. The large number of subjects studied provided additional information on the range of variation of intestinal motility, biological availability of strontium, cesium and barium following ingestion of fallout, and retention of the radionuclides of these elements.

THE CONSEQUENCES OF INGESTION BY MAN OF REAL AND SIMULATED FALLOUT

Part I. Introduction

In 1961 concern about some of the problems of the internal deposit of fission products (FP) following ingestion of local fallout led us to propose studies using real fallout from the Nevada Test Site (NTS); simulated fallout particles that contained Sr^{85}, Ba^{133}, or Cs^{134}; and solutions of $Sr^{85}Cl_2$ and $Cs^{134}Cl_2$. The proposal involved feeding the test materials to healthy adult volunteers and estimating retention and absorption from measurements of their gamma radiation using the whole body spectrometer (WBS) of the Argonne Cancer Research Hospital. The results reported here are concerned with the transit time of particles in the gastrointestinal tract (Part II); the biological availability of radioactivity following ingestion of real local fallout (Part III); and the extent to which the process of leaching from simulated fallout may modify the metabolic behavior of strontium, cesium and barium (Part IV).

The fallout that we studied and attempted to simulate is designated variously as local, early, or close-in. After land-surface detonations in the United States at the NTS such fallout consists of particles ranging in size from less than 1 micron in diameter to more than 1 millimeter. The particles are composed of FP, and soil materials and components of the nuclear device in which radioactivity has been induced by neutrons. Near the point of detonation the particles are large and silicaceous with radioactivity distributed throughout and condensed on the surface. The ratio of biologically available activity to total radioactivity is reported to be small. As one moves away and downwind from the point of detonation the particles become smaller, relatively more of the radioactivity is condensed on their surfaces, and biological availability of the FP is increased. The extent of the distribution of fallout depends on the size of the nuclear explosion, meterological conditions, and the relation of the fireball to the surface of the earth. With high-yield thermonuclear weapons under average weather conditions local fallout may extend to distances exceeding 500 miles, and the area contaminated by a single weapon may exceed thousands of square miles.

The principal hazard from this variety of fallout is external exposure to gamma radiation, the intensity of which may exceed 1,000 r/hour in some locations at the time when fallout is completed. The risk of internal deposition of FP is real but the magnitude of the risk is uncertain. Fallout particles enter the body by inhalation and ingestion. Because of the relatively large size of the particles, the majority of those inhaled are promptly trapped in mucus and quickly cleared from the respiratory passages either to be expectorated or swallowed. Fallout ingested with food or water (plus that from the respiratory tract) passes through the gastrointestinal system where the particles are exposed to a changing chemical environment in which some fraction of the FP may be dissolved and thus become available for absorption and subsequent deposition in internal organs and tissues.

The factors responsible for absorption of FP determine the biological availability of the radionuclides in fallout. These factors include: (1) the physical and chemical characteristics of the particles, i.e., the leachability and solubility of the nuclides they contain; (2) the absorba-

bility of the chemical compounds formed in the intestinal contents; and (3) the transit time of particles through the gastrointestinal tract. Various estimates have been made of the biological availability in man of local fallout. According to ENW[1] 10 per cent of FP in local fallout is available, but there are no experimental data to support this estimate. Miller[2] has calculated the potential solubility of the principal nuclides as a function of particle size. In the case of I^{131} the estimate ranges from 0.016 (fraction soluble) for particles deposited close to the detonation, to 1.0 for the more distant ones. For Sr^{90}, theoretical solubility ranges from 0.16 close in, to 1.0 at the outer limits of the distribution.[3] The chemical solubility of local fallout collected at NTS after tests of various nuclear devices ranges from nil to more than 50 per cent. Some writers assume that biological availability parallels the chemical solubility in dilute solutions of acids. In some estimates of the hazard from ingested fallout the biological availability is taken as equal to the abundance of a particular radionuclide.

The possibility of obtaining suitable simulants for fallout occurred to us after reading a report[4] that described the 'radiating microspheres' developed by the Minnesota Mining and Manufacturing Co. (3 M). These are "ceramic bodies of spherical shape and selected size which contain and immobilize relatively large quantities of many useful isotopes." In reply to our inquiry, T. N. Lahr of the 3 M Radiochemical Project said that he could make microspheres in which a radionuclide would not be completely immobilized so that some fraction would leach out in a weak acid solution. In December 1961 two of us (JHR and GVL) met with a group of scientists interested in fallout at AEC headquarters in Germantown. The group (Kermit Larson, J. Z. Holland, W. E. Lotz, H. D. Bruner, S. H. Cohn, and J. S. Robertson) agreed that it should be possible to prepare satisfactory simulants with the following properties: The close-in simulant should be glassy or ceramic, and about 10 per cent of the radioactivity should be leachable; the distant simulant should resemble a sintered oxide with a solubility of about 70 per cent; a suitable particle size would be in the range: 20 to 60 microns in diameter. In addition the group agreed that the proposed studies were feasible and worth doing, and that the elements of greatest interest were strontium, cesium and barium.

The radionuclides of these elements (and iodine) in FP are considered critical nuclides because metabolic processes lead to concentration in bone, muscle, and the thyroid gland. Once concentrated, each turns over slowly so that the combination of selective deposition, long effective half-life (with the exception of I^{131}) and energetic nuclear radiations can result in a significant internal radiation dose. The estimate of internal dose following ingestion is based on assumptions regarding the fraction absorbed, the fraction of the amount absorbed that goes to the target organ, and the rate of removal from the target organ. For most purposes the values assigned to these assumptions are those given in ICRP Publication No. 2,[5] and listed in Table I-1. Although these are convenient averages the fact is that absorption, concentration in a target organ, and biological turnover may be profoundly modified by such factors as the motility of the gastrointestinal tract, the chemical compounds formed in the intestinal contents, the route of administration which may regulate the amount that goes to the target organ, and the physiological state of the individual.

There is an extensive literature on fallout, most of which deals with (1) the external radiation hazard from local fallout; (2) the body burden of critical nuclides in animals collected near a test site; (3) the movement through the biosphere of critical nuclides from local as well as world-wide fallout; and (4) the metabolism of iodine, strontium and cesium following oral and

Table I-1

BIOLOGICAL AND RELATED PHYSICAL CONSTANTS

Element and radio-nuclide	Average daily intake (g/day)	Organ of reference	Half-life (days)			Fraction from GI tract to blood	Fraction from blood to organ of reference	Fraction reaching organ of reference after ingestion	Γ r/hr-mc at 1 cm	$\overline{E}_\beta$ Mev
			Physical Tr	Biological Tb	Effective T	f_1	f_2'	f_w		
Sr	10^{-3}	Total body		1.3×10^4		0.3	1.0	0.3		
Sr^{85}		Total body	65	1.3×10^4	64.7	0.3	1.0	0.3	3.2	0.014
Sr^{85}		Bone	65	1.3×10^4	64.8	0.3	0.7	0.21		
I	2×10^{-4}	Thyroid		138		1.0	0.3	0.3		
I^{131}		Thyroid	8		7.6	1.0	0.3	0.3	2.18	0.19
Cs	Trace	Total body		70		1.0	1.0	1.0		
Cs^{134}		Total body	840	70	65	1.0	1.0	1.0	8.0	0.116
Ba	9×10^{-4}	Total body		65		0.05	1.0	0.05		
Ba^{133}		Total body	2.6×10^3	65	63	0.05	1.0	0.05	2.0	0.014
Ba^{133}		Bone	2.6×10^3	65	63	0.05	0.7	0.035		

Source: Table 12, Report of Committee II, ICRP;[5] and Hine and Brownell.[14]

parenteral administration of solutions, and after accidental contamination. We are not aware of any report of the feeding of real, local fallout to volunteers. To our knowledge this is also the first study where strontium, cesium or barium were administered in a fashion that simulated the actual ingestion of particulate fallout. Since it was debatable if there was any advantage to the use of simulants, an important objective of our study was to compare the behavior of radionuclides leached from the simulant with that of simple solutions of strontium and cesium.

Plan of Experiments and Methods

The design of the experiments was simple: whole body counting was used to measure the amount of γ-emitting activity that remained in the bodies of the volunteers at intervals after ingestion of the test materials. The real fallout and the simulants were swallowed in gelatin capsules: the solutions of $Cs^{134}Cl_2$ and $Sr^{85}Cl_2$ were swallowed with several ounces of water. All test materials were administered without regard to meals or time of day. The identity and the amount of the radionuclide in each dose was determined by one of us (GVL) before administration using an Autogamma γ-ray spectrometer. Immediately before the dose was taken, the body background of the subject was measured for 40 to 60 minutes in the WBS. At some time during the few hours following the dose—and before the subject voided—a 2-minute whole body count was made. The net counting rate at the time of the first post-dose count was taken as 100 per cent of dose for the purpose of calculating retention at later times. Thereafter, at intervals that varied from a few days to a few weeks serial whole body counts were made: the counting time was adjusted to the amount of activity remaining so that the probable error of counting was small. Serial counts were continued until: (1) the net counting rate decreased to less than 1.0 per cent of the first post-dose count, (2) sufficient counts were obtained for a reliable estimate of rate of excretion, or (3) the volunteer was no longer available. In a few cases samples of stool and urine were collected during the first few weeks after simulants were fed, and these were measured in a properly calibrated large-volume well counter. The information from these measurements was not commensurate with the effort expended and collections of excreta were discontinued early in the study.

The volunteers were healthy adults—University students and members of our staff—who were properly informed of the nature of the experiments and the implications of the study for Civil Defense. None reported any gastrointestinal symptoms following ingestion of any of the test materials. The experiments were approved by the Committee for the Human Use of Radioisotopes of the University of Chicago Hospitals and Clinics. The total number of volunteers was 102.

All measurements of radioactivity retained in the subjects were made with the whole body gamma-ray spectrometer (WBS) of the Argonne Cancer Research Hospital. This instrument, which has been described in detail elsewhere[6] consists of four 5 x 5 inch thallium-activated Na I crystals coupled to photomultiplier tubes arranged above a couch in an iron-shielded room. The output of each crystal detector is transferred through a mixing circuit to a multi-channel pulse height analyzer adjustable for readouts of 3, 6 or 12 Kev per channel. The readout is stored on punched paper tape. When the volunteers were counted the 4 crystals were placed approximately equidistant from each other along the midline of the subject and 18.5 inches above the couch. For one-half the counting time the subject was supine: for the other half prone. Preliminary trials demonstrated that there was only a few per cent difference in the efficiency with

which the WBS measured a point source (such as a capsule) inside a subject's body and the same amount of activity distributed throughout the body as an extended source. The practice of counting in the prone and the supine position adequately compensated for any inequality in the anterior-posterior distribution of radioactivity in the course of an experiment.

The Argonne instrument is quite stable: 22 daily counts of a standard Sr^{85} source (4 vials containing a total of 0.57 μc) gave a mean of 12,398 ± 190 net cpm. Variations of the background of the iron-shielded room were equally small, and when contamination occurred it was cleaned up promptly.

The dead time of our WBS is corrected for automatically by a proportional increase in the live time of the duty cycle. At counting rates less than about 500,000 cpm the response of the instrument is a linear function of the amount of radioactivity present. Since few of our counts exceeded 100,000 cpm no correction for coincidence was necessary.

The background counting rate of the iron-shielded room was measured each day by a 40 or 60 minute count, and the performance of the detectors was checked using a sealed calibrated source that contained 2.0 micrograms of Ra^{226} in equilibrium with its daughters.* The efficiency of the WBS for the various test materials and for the energy ranges used to count them is shown in Table I-2.

Table I-2

RESPONSE OF WHOLE BODY SPECTROMETER

Radionuclide:	Sr^{85}	Cs^{134}	Ba^{133}	Ra^{226}[a]
Photopeak of characteristic γ-radiation, Mev	0.510	0.605; 0.796	0.302; 0.355	0.610
γ-photons/dis[b]	(1)	(.85) (.77)	(.26) (.74)	
Energy range over which counts were summed, Mev	0.378-0.570	0.504-0.900	0.198-0.432	0.528-0.708
Background, room plus average subject, cpm	340	465	684	
Calibration factor,[c] net cpm/μc	13,200	16,940	6,160	14,450
Efficiency of detector, %[d]	0.59	0.96	0.38	0.65

Notes:

(a) This was a sealed calibrated source containing 2.0 micrograms of Ra^{226} in equilibrium with its daughters, obtained from the U.S. National Bureau of Standards.

(b) Source: Hine and Brownell.[14]

(c) Net cpm per μc ingested.

(d) Efficiency = $\frac{\text{net cps}}{\gamma\text{-photons/sec}}$ x 100. Photon yield for Cs^{134} was taken as 0.8, for Ba^{133} as 0.74.

*Supplied by the National Bureau of Standards.

Processing the Data

The fraction of dose retained at any time, t, days was:

$$\frac{\text{net cpm at t}}{\text{net cpm at } t_o} = f_R \ (*) \qquad \text{Eq. I-1}$$

where t_o is the time of the first count after the dose was swallowed.

The fraction of dose absorbed, f_A, was obtained from serial whole body counts made during the 2nd through the 6th week after the dose was given. We assumed that 99+ per cent of ingested insoluble material was eliminated from the intestinal tract before the end of the 7th day (see Part II). Furthermore we assumed that excretion by any route of radioactivity absorbed occurred at a single exponential rate for about the first 50 days. Using the serial values for whole body net cpm plotted semilogarithmically, the y-intercept for day 1 (the day after the dose was given) was obtained by extrapolating a line fitted by eye for the period 7 to 50 days. The fraction of dose absorbed was:

$$f_A = \frac{\text{extrapolated net cpm at day 1}}{\text{observed net cpm at } t_o} \qquad \text{Eq. I-2}$$

Although it is the convention to assume that biological elimination of most elements follows a simple exponential function, it is well known that many data support the view that the fraction of the body burden excreted per day may vary inversely with time and may be best represented by a power function. Following a single injection of certain bone-seeking radionuclides—such as those of strontium and barium—the body burden can be expressed as:

$$R(t) = At^{-n} \ , \quad t \geq 1 \text{ day} \qquad \text{Eq. I-3}$$

where R(t) = fractional retention t days after injection; A = normalized fraction of injected dose retained at the end of unit time; and n = a constant.

We have chosen not to employ this expression for individual subjects because there is some indication that a power function does not represent precisely the true situation, since the exponent n has been found to vary with time. In addition to this, its metabolic significance remains unexplained. For the sake of simplicity we expressed long term retention of strontium, barium and cesium as the per cent of the amount absorbed (f_A) remaining in the body at times longer than 50 days. In the case of cesium where elimination appears to follow a simple exponential function indefinitely, the rate of elimination is reported as the half-time in days.

The results obtained by graphical analysis of the whole body counting measurements were verified by an independent machine analysis using routine programs available in the Computation Center of the Biological Sciences Division.

Part II: Transit Time of Particles Through the Human Gastrointestinal Tract

It is common knowledge that the time required for some recognizable articles of the diet (corn, for example) to appear in the feces varies from a matter of hours to several days. In fact, the variation in intestinal motility of healthy people is so great that few clinicians will

*The symbols f_R and f_A were selected because they do not duplicate any of the symbols used in ICRP Publication No. 2.[5]

agree on an average time for half or all of a suitable indicator to pass through the gut. For radiological health purposes, most workers use the assumptions proposed for the Standard Man which are given in Table II-1. These were not particularly useful for our purpose since we were less concerned with the radiation dose to portions of the gut than we were about the time at which we could confidently expect that 99 per cent or more of ingested particulate material had

Table II-1

THE GASTROINTESTINAL TRACT OF THE STANDARD MAN

Portion of interest	Mass of contents, grams	Time food remains, hours	Suggested revision, hours
Stomach	250	1	1
Small intestine	1100	4	4
Upper large intestine	135	8	13
Lower large intestine	150	18	31

Note: Hayes, Carlton and Butler[7] studied the elimination of an insoluble tracer and suggested changing the entrance time into the lower large intestine from 13 to 18 hours; and the in-residence time in the lower large intestine from 18 to 31 hours.

Source: Table 11, Report of Committee II, ICRP.[5]

been excreted. The Standard Man value—an average of 31 hours from ingestion to excretion—is obviously too short and does not provide any indication of the variability which must occur. We were interested in obtaining a reliable value for the 99-per cent excretion time because we could then assume that any radioactivity subsequently remaining represented nuclides released from particles and absorbed from the intestinal tract minus the fraction of absorbed activity excreted in urine and feces up to that time. Obviously it was to our advantage to start making serial measurements to estimate the rate of excretion of absorbed material as soon as possible after the dose was administered. In this report, then, we define transit time as the time required to excrete more than 99 per cent of a dose of insoluble material.

When we began this study the report of Hayes, Carlton and Butler[7] had not yet been published. The only guidance available to us was the experience of several groups of investigators with oral doses of Fe^{59} to study iron absorption using whole body counting. There was general agreement among them that all of the unabsorbed tracer was excreted by 10 to 14 days. The experiments reported here were designed to find a time between 31 hours and 10 days which would satisfy our requirements. In addition to information about the distribution of transit times we were interested to find out if any significant fraction of insoluble particles was trapped in anatomical features of the gut such as the vermiform appendix. Finally we wanted to know if the stable microspheres were as insoluble in vivo as in vitro.

Materials and Methods

Radiating microspheres containing Sr^{85} or Cs^{134} or Ba^{133} were prepared for us by the Radiochemical Project of the Minnesota Mining and Manufacturing Company to be used as insoluble controls for the simulants of fallout. The microspheres are milky white in appearance and almost perfectly spherical in shape. They have an absolute density of about 3.0 g/cm^3, and a

bulk density of 2. They are completely ceramic in nature and have a melting point in excess of 1500° C. They are physically insoluble in all organic and inorganic solvents except boiling 57% HF. Soak tests in water and in 0.01 N HCl for 7 days at 50° C demonstrated slight leaching of the nuclide label: on the order of 0.001 to 0.004 per cent.[4] The specific activity was about 50 μc/gram, and the particle size was in the 30 - 40 micron range.

Three groups of volunteers—14 in all—were used for a pilot study to see if there was any retention of radioactivity at 10 and 20 days after ingestion of the labeled microspheres. On the basis of these results, three additional groups (a total of 12) were fed Cs^{134} labeled microspheres and counted every 2 days until the amount of activity remaining was less than 0.1 per cent of the dose. Some of the subjects were asked to keep diaries recording their bowel movements: this information was less important than the counting data so the practice was discontinued.

The amount of radioactivity fed—from about 0.5 to 14.0 microcuries—was a compromise: on the one hand we were obligated to keep the radiation dose to the gut to a minimum; and on the other hand we wanted to use sufficient activity so that retention of less than 1.0 per cent could be measured with an acceptable probable error.

Results

The counting data for the three pilot studies are shown in Table II-2. In Experiment #7 the amount of Sr^{85} microspheres fed was so small that the probable error of the net counting rate (PE) if 1.0 per cent of the dose remained (e.g., about 55 net cpm) was 4.9 per cent. When the net cpm on D + 10 and D + 20 are corrected for decay it appears that the average retention was about 1.5 and 1.0 per cent of dose, respectively. From these data alone it is not possible to decide if the fraction that remained represents microspheres trapped in the gut, or radiostrontium leached from the supposedly insoluble microspheres and absorbed from the intestinal contents.

In Experiment #9 when larger amounts of Ba^{133} microspheres were fed, the net counting rates on D + 11 and D + 23 were distinctly less than the standard error (SE = $\sqrt{\text{cpm}}$) of the background counting rate: 26 cpm. In this case we concluded that no microspheres remained in the gut, and that no Ba^{133} had been leached from the particles and absorbed.

With the Cs^{134} microspheres (Experiment #1) the fraction of activity remaining on D + 10 and D + 20 was less than in the case of Sr^{85} but may be significant. The PE of these net counting rates was less than 5 per cent, and in every case the observed net cpm was several times the SE of the background counting rate: 25 cpm. Since it is unlikely that any microspheres remained in the gut as long as 20 days, we concluded that some radiocesium—less than 0.2 per cent—had leached from the particles and been absorbed. The net counting rates were so low, however, that it was not feasible to attempt an estimate of the fraction of leached material that was absorbed.

The pilot study was satisfactory because the results indicated that the upper limit of the distribution of transit times was less than 10 days.

The results of 3 additional experiments with Cs^{134} microspheres are given in Table II-3. Here the findings are expressed as per cent of dose remaining on Days +2, +4, +6, +8, and +10. The data indicate that on the average about 60 per cent of the particles were excreted during the first 48 hours following ingestion. The range, however, was quite large: from 2 to 100 per cent

Table II-2

EXCRETION OF STABLE MICROSPHERES

Subject	Tracer	Day 0 net cpm	Day + 10		Day + 11		Day + 20		Day + 23
			Net cpm[a]	f_R[b]	Net cpm	f_R	Net cpm	f_R	Net cpm
7-1	Sr^{85}	6,886	59	.0085			46	.0066	
7-2	Sr^{85}	4,688	44	.0093			38	.0081	
7-3	Sr^{85}	5,475	63	.0115			68	.0145	
7-4	Sr^{85}	5,827	56	.0102			48	.0087	
7-5	Sr^{85}	4,565	78	.017			54	.0118	
9-1	Ba^{133}	86,221			18	<.001			-
9-2	Ba^{133}	141,379			3	<.001			nsc[c]
9-3	Ba^{133}	132,407			nsc				-
9-4	Ba^{133}	123,414			10	<.001			-
1-1	Cs^{134}	199,835	79	<.001			68	<.001	
1-2	Cs^{134}	242,053	110	<.001			85	<.001	
1-3	Cs^{134}	190,692	56	<.001			75	<.001	
1-4	Cs^{134}	262,418	92	<.001			89	<.001	
1-5	Cs^{134}	271,314	593	.021			72	<.001	

Notes: Probable error[d] for f_R = .01 of dose: (1) For Sr^{85} = 55 net cpm; PE = 4.9 per cent, (2) For Ba^{133} = 1,200 net cpm; PE = 0.4 per cent, (3) For Cs^{134} = 2,330 net cpm; PE = 0.3 per cent.

Standard error[e] of background rate: (1) For Sr^{85} experiment = 17 cpm; (2) For Ba^{133} experiment = 26 cpm; (3) For Cs^{134} experiment = 21 cpm.

(a) Net cpm not corrected for decay.

(b) f_R = fraction of dose remaining.

(c) nsc = No significant counts: i.e., equal to or less than background rate.

(d) $PE = \frac{67.45}{\sqrt{G}} \left(\frac{\sqrt{K^2 + K}}{K - 1}\right)$, where G = gross counts; and $K = \frac{\text{gross cpm}}{\text{background cpm}}$.

(e) $SE = \sqrt{cpm}$

remained. By the 6th day less than 0.1 per cent of the dose was still retained by 10 of 12 subjects. Combining the results of these three experiments with those of Experiment #1 (Table II-2) we see that by the 10th day only 3 of 17 subjects retained more than 0.1 per cent of the dose of Cs^{134}. The actual values for these were 202, 593 and 895 net cpm, respectively, i.e. 0.19, 0.22 and 0.95 per cent of the dose.

Discussion

Our findings indicated that we could begin serial measurements in the WBS to evaluate absorption as early as the 6th day after the dose was swallowed if we were willing to accept a small amount of uncertainty because of individual variations. By waiting a day or two longer the likelihood became substantially less that any particulate material remained in the gut. Our re-

Table II-3

EXCRETION OF Cs^{134} MICROSPHERES

Subject	Per cent of dose remaining on day +				
	2	4	6	8	10
1	54	<.1	<.1		
2	67	<.1	<.1		
3	69	2.5	<.1	<.1	
4	2	0.2	<.1	<.1	
5	8	0.3	<.1	<.1	
6	8	<.1	<.1		
7	12	0.1	<.1	<.1	
8	20	<.1	<.1		
9	53	2.5	<.1	<.1	
10	9	9.0	<.1	<.1	
11	100	83.0	26.0	6.0	0.2
12	94	12.0	-	-	0.9
Average[a]	41	9.0	2.5	0.6	0.2
Average, without #11	36	2.5	<.1	<.1	<.1
Median	20	0.3	<.1	<.1	<.1

Note: To calculate averages, <.1 = 0.1

sults suggest that the Standard Man assumption of 31 hours as the average time that ingested material remains in the intestinal tract (Table II-1) is too short, thus leading to underestimates of radiation dose to the intestinal mucosa from ingested radioactivity. There does not appear to be any simple way to use the data obtained by whole body counting to adjust the Standard Man assumptions.

It is interesting to compare the findings of Hayes, et al.[7] with those presented here. They fed an insoluble tracer, La^{140} citrate, to 54 patients and measured the radioactivity in each stool as it was passed. For each subject at least 90 per cent of the dose was recovered ultimately. A graph from their report showing cumulative excretion as a function of time after ingestion is redrawn as Figure II-1. On the same figure there is a comparable curve showing the average fraction of dose remaining in our subjects. Hayes, et al. state that for radioactive material with a half-life longer than about 12 hours the Standard Man assumptions require revision. An average residence time of 49 hours fits their data better than the published value: 31 hours. Reading the points off their curve (Figure II-1) it appears that about 60 per cent of the activity was excreted during the first day; and the time for 98 to 99 per cent excretion was about 4 days. It is evident that bowel motility was somewhat more rapid in their patient-subjects than in our healthy active volunteers. Perhaps bowel habits are more regular in hospital than elsewhere. Actually the difference in intestinal motility of the two groups is not very important. Had we used their data to determine the time when less than 1 per cent of the dose of insoluble material remained in the gut we would have selected the 5th or 6th day. On the basis of the results presented here we waited about 48 hours longer before we assumed that excretion of insoluble particles was complete—that is, that less than 1 per cent of the dose remains.

The 3 M stable radiating microspheres were described by the manufacturer as insoluble. Some leaching occurred in vitro, however, when tracer-labeled microspheres were submitted

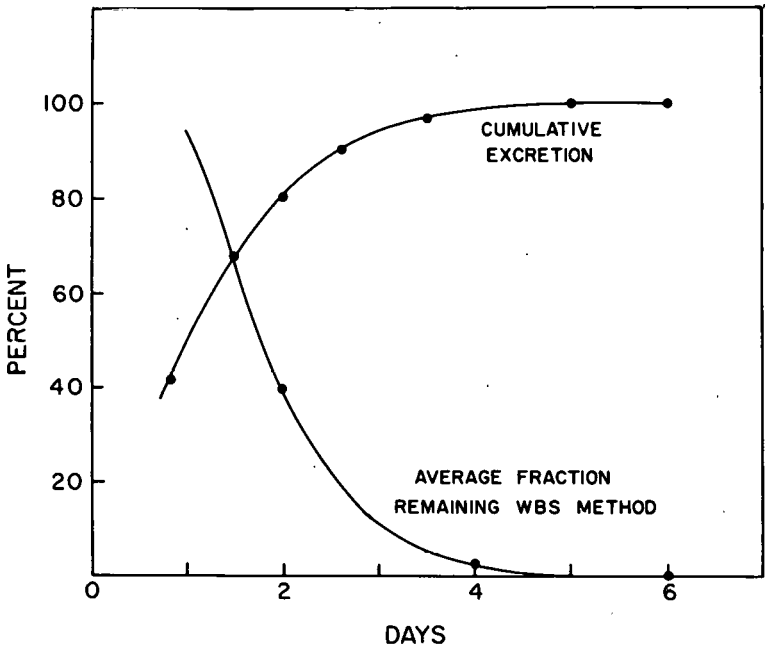

Figure II-1. Transit time of particles in the human intestinal tract. The upper curve is the cumulative excretion of La^{140} citrate by hospitalized subjects whose median age was less than 53 years. This curve is redrawn from Hayes, Carlton and Butler.(7) The lower curve is the average for 12 of our subjects who received Cs^{134}-microspheres (Table II-3).

to a soak test. In the case of Cs^{137} and Sr^{90} microspheres, for example, the manufacturer reported that the leach rate was the same in water and in dilute HCl. In prolonged tests "leaching continues at a constant rate after 7 - 14 days, and is independent of sample size and solvent volume within reasonable limits."(4) Our data suggested that more leaching occurred in the intestinal contents of man than in vitro. After 7 days it appeared that about 1 per cent of Sr^{85} had been retained. In other experiments (see Part IV) when a dilute aqueous solution of $Sr^{85}Cl_2$ was fed the fraction absorbed was about 17 per cent. Such being the case it is proper to assume that as much as 4 or 5 per cent of the radiostrontium leached out of the 'stable' Sr^{85} microspheres during their residence in the gut. This is much more than the 0.001 per cent reported for soak tests using Sr^{90} microspheres prepared in the same fashion as the ones we used. Our own soak tests (Table IV-1) were performed with 0.1 N HCl and 0.1 N NaOH at 37° C for 2 hours. No measurable activity was leached from any of the stable microspheres. The procedure used could detect at least 0.001 per cent of the activity present. We have no information about the physiological mechanisms that are responsible for the discrepancy between the in vivo and the in vitro results.

When solutions of $Cs^{134}Cl_2$ were fed (see Part IV) about 90 per cent of the tracer was absorbed. The amount of radiocesium leached from the Cs^{134} microspheres and absorbed ranged from about 0.03 to 0.2 per cent. This is significantly more than the 0.004 per cent reported by the manufacturer for Cs^{137} microspheres manufactured in the same fashion as those supplied to us.

The radiation dose to the lower large intestine was calculated using 31 hours as the average in-residence time. The largest dose was 696 mrads, and the average was less than one half that amount. The estimates of radiation dose for all experiments are given in Table II-4.

Part III: The Availability of Radionuclides in Local Fallout

The biological availability for man of the radioactivity contained in local fallout is not well documented. The factors that determine availability include: (1) the physical and chemical characteristics of the particles, i.e., the leachability and solubility of the nuclides they contain; (2) the absorbability of the chemical compounds formed in the intestinal contents; and (3) the transit time of particles through the gut. It is customary to assume that 10 per cent of the activity of local fallout that is swallowed is available. Measurements of the fraction of activity leached by acid, alkaline and neutral solutions have been reported that range from none to more than 50 per cent. Such data display wide variations depending on particle-size, solvent, age of the material, duration of contact with the solution, and conditions associated with the nuclear explosion. The present study was undertaken to measure the biological availability of activity in local fallout collected at a single location following the land-surface detonation of a nuclear device: SMALL BOY, on July 14, 1962 at the Nevada Test Site of the United States Atomic Energy Commission.

Material and Methods

The samples of fallout were sent to us by Carl F. Miller (Stanford Research Institute) with the approval of the Office of Civil Defense. The material we received on D + 5 had the characteristics shown in Table III-1A. For the feeding experiments only samples #4, 5, 6, 7, and 8 were used. According to Miller the fallout was collected at a distance of 4,500 feet (1.390 m) east of the site of detonation. The radiation intensity of the fallout field at that location, corrected to H + 1 hour was 34 r/hour. There were no measurements of the solubility of the samples we received, but data are available for other collections at nearby stations. These are also given in Table III-1B.

Portions of each sample were placed in gelatin capsules and swallowed by 10 healthy volunteers. At the time of ingestion (on D + 6, D + 7, or D + 9) the gross gamma activity of each dose was equivalent to about 1.2×10^5 disintegrations per second. This amount of activity was selected because: (1) we assumed acid-solubility was about 10 per cent; (2) we assumed the factor for the decay rate was approximately $t^{-1.2}$; (3) the beta:gamma ratio was taken to be unity; (4) we did not want the radiation dose to the lower large intestine to exceed 100 mrad;* and (5) we wanted to give enough activity to provide reliable counting rates during the 3rd and 4th weeks after ingestion.

For these studies the output of the WBS was summed into 6 energy ranges as shown in Table III-2 and Figure III-1. When the subjects were counted the crystal arrangement was as described in Part I. When aliquots of the samples of fallout were counted the crystals were arrayed in a cluster directly over the source. Correction factors for radioactive decay were obtained by counting aliquots of samples #4, 5, 6, 7, and 8 at frequent intervals between D + 11 and D + 39.

*To approximate this dose we followed Dunning[8] who calculated that 48 microcuries of 1-day old fallout would deliver about 1.0 rad to the lower large intestine.

Table II-4

AMOUNTS ADMINISTERED AND ESTIMATES OF RADIATION DOSE

Test material	Number of subjects	Amount administered μc		Estimates of radiation dose, mrads					
				To mucosa of lower large intestine[a]		To whole body[b]		To bone and bone marrow[b]	
		Minimum	Maximum	Per μc	Maximum[c]	Per μc	Maximum[c]	Per μc	Maximum[c]
Real fallout	10	0.2	0.7	-	-	-	-	-	-
Strontium-85				11.7	20	13.9	10.4	36.4	19
Microspheres	5	0.4	0.6						
Local simulant	13	0.9	1.5						
Distant simulant	9	0.7	1.3						
$Sr^{85}Cl_2$	18	0.9	2.5						
Cesium-134				49.7	696	42.8	165	-	-
Microspheres	18	5.5	14.0						
Local simulant	5	7.0	9.0						
Distant simulant	5	2.4	4.7						
$Cs^{134}Cl_2$	4	0.5	0.6						
Barium-133				9.3	214	10.3	11	28.6	21
Microspheres	4	13.5	23.0						
Local simulant	3	4.0	6.0						
Distant simulant	8	4.0	7.0						
Total:	102								

Notes: (a) Mucosa dose: $d(\beta + \gamma)/hr = 0.5\ C\ (2.13\ \overline{E}_\beta + 10^{-3}\ \overline{g}\ \Gamma)$ rads, using 31 hours for residence time.

(b) Whole body and bone + bone marrow: $D_{\beta + \gamma} = C\ T\ (73.8\ \overline{E}_\beta + 0.0346\ \overline{g}\ \Gamma)$ rads, using T from Table I-2. These formulas are from Quimby et al.[15]

(c) Factors used to estimate maximum radiation dose to any subject, from Table I-2 or experimental data, whichever was larger

Sr^{85}, whole body = 0.3 x 2.5 x 13.9; bone = 0.21 x 2.5 x 36.4; LLI = 0.7 x 2.5 x 11.7.

Cs^{134}, whole body = 0.82 x 4.7 x 42.8; LLI = 14 x 49.7.

Ba^{133}, whole body = 0.15 x 7 x 10.3; bone = 0.105 x 7 x 28.6; LLI = 23 x 9.3.

Table III-1

A. CHARACTERISTICS OF THE FALLOUT SAMPLES[a]

Size-sample number	Size, microns	Mass, grams	Activity, as per cent of total
1	2830 +	-	-
2	2830 - 1410	.0528	14.7
3	1410 - 710	.2016	22.4
4	710 - 350	.2051	26.2
5	350 - 177	.0674	23.9
6	177 - 88	.0630	4.9
7	88 - 44	.2356	2.8
8	44 - 0	.3880	5.1

B. SOLUBILITY OF COMPARABLE SAMPLES[b]

Mesh size	Age of material days	Time of contact with acid,[c] days	Per cent leached[d]
+24	5.9	10.1	8.5
+42	5.9	10.1	3.8
+80	5.9	10.1	19.0
+170	5.9	10.1	42.0

Notes:

(a) Description of Collection Number 100 PC 5 (SIS PC 5), supplied by C. F. Miller.

(b) This is another collection from the same location as 100 PC 5.

(c) HCl solution at pH 1.0.

(d) γ-activity only.

- Another sample from the same location, was tested when 1.1 days old: acid-solubility ranged from 20 to 58 per cent.

These measurements, corrected for background, are shown as a log-log plot in Figure III-2. The curves, which are linear, were fitted by eye and extrapolated back to the time the fallout samples were fed. A decay correction factor for each subject was obtained in the following manner: If the sample was fed on D + 6 the corresponding value for net cpm was read off Figure III-2 (see the arrows on Curve #7) at the midpoint between 6 and 7 days (315,000), and the 14-day value was read off at the midpoint between 20 and 21 (66,000). The factor used in the case of LO was (315,000/66,000) 4.8. Individual decay factors were calculated for each sample and for the time period involved in each experiment.

Results

Net counting rates in the 6 energy ranges for each of the samples are shown in Table III-2. In spite of the wide variation in particle size (#4 = 350 - 710 microns, and #8 = less than 44 microns) there appear to be only minor differences in nuclide composition as evidenced by the fraction of activity in each energy range. This conclusion is supported by the spectra of 4 of the 5 samples following ingestion as shown in Figure III-1. (A satisfactory curve for sample #4 is not available.) Of these spectra only that of #6 shows a major difference: there is a prominent peak in energy range E at about 1.1 Mev which is not present in the others. Additional evi-

Table III-2

COUNTING RATES OF SAMPLES ON D + 11, NET CPM*

Range:	A	B	C	D	E	All
Channels:	16 - 46	46 - 68	68 - 106	106 - 144	144 - 208	16 - 208
Mev:	0.096 - 0.276	0.276 - 0.408	0.408 - 0.631	0.631 - 0.864	0.864 - 1.25	0.096 - 1.25
Room Background	823 (0.51)	244 (0.15)	270 (0.17)	137 (0.08)	149 (0.09)	1,623
#4	16,169 (0.37)	5,910 (0.13)	9,611 (0.22)	10,942 (0.25)	1,376 (0.03)	44,008
#5	36,080 (0.36)	16,370 (0.17)	25,035 (0.25)	17,015 (0.17)	4,935 (0.05)	99,435
#6	15,031 (0.36)	7,176 (0.17)	10,477 (0.25)	7,094 (0.17)	2,093 (0.05)	41,871
#7	24,687 (0.35)	13,128 (0.19)	17,900 (0.26)	10,951 (0.16)	3,602 (0.05)	70,268
#8	13,015 (0.34)	8,102 (0.21)	9,938 (0.26)	5,095 (0.13)	1,953 (0.05)	38,103
Average fraction per energy range:	(0.356)	(0.174)	(0.247)	(0.176)	(0.047)	

*Figures in parenthesis show fraction of counts in an energy range.

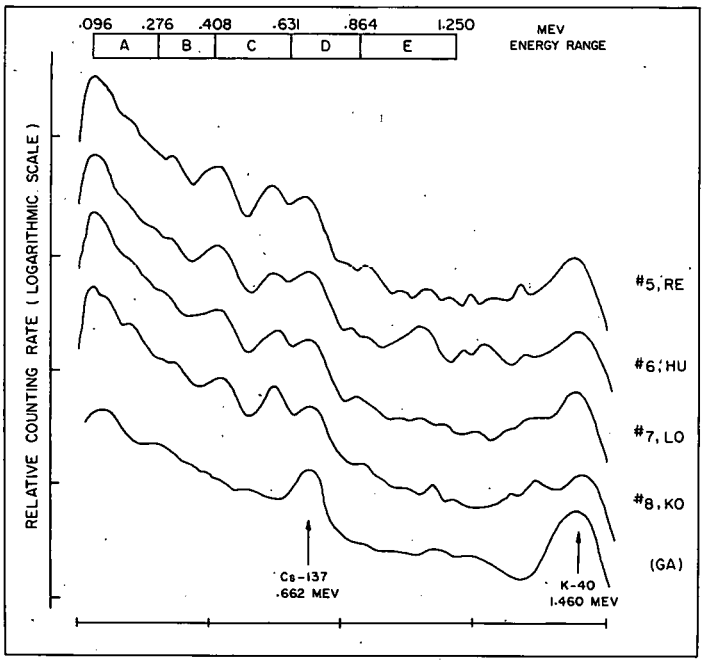

Figure III-1. Gamma-ray spectra after ingestion of real fallout. The counts for these spectra were summed for 12 Kev per channel. The upper 4 curves were obtained 1 - 2 days after fallout was ingested. The lower spectrum (GA) is from a control subject and is included to demonstrate the resolution of the WBS.

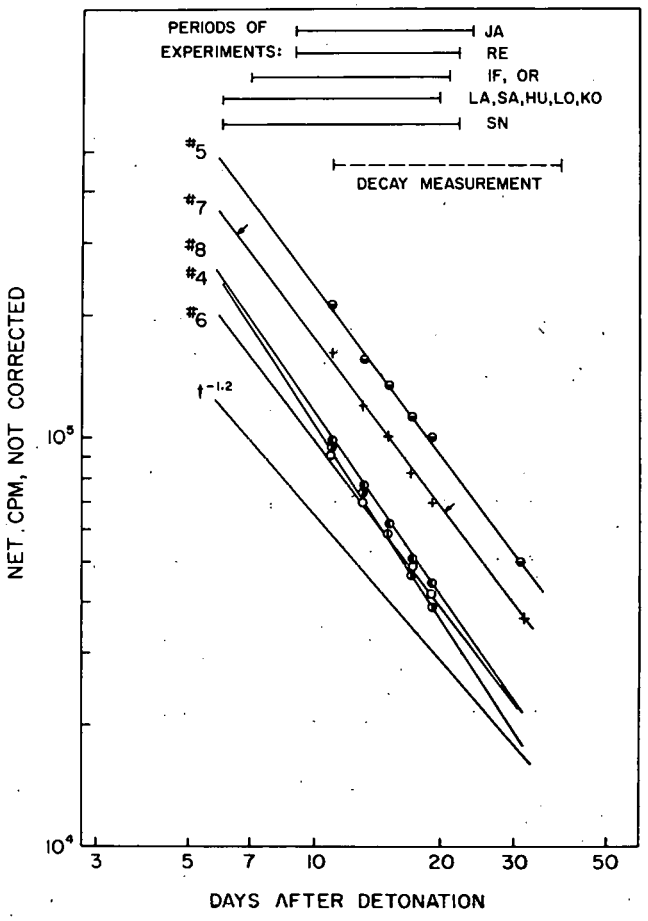

Figure III-2. Decay rate of samples of real fallout.

dence for minor variations in the radionuclide composition of the different sized samples is seen in Figure III-2 where one can note variations in the decay rates of the 5 samples. The factors used to correct for decay are given in Table III-3.

The results of the measurements of all 10 subjects are summarized in Table III-3. The values for f_R—the fraction of dose retained on the last day—represent the amount of activity absorbed from the gut minus the fraction of absorbed material that was excreted up to the time of the final count. The values for f_A—the fraction of dose absorbed—were estimated from f_R multiplied by an arbitrary constant, c = 1.35. This constant was derived from our study of simulated fallout that is described in Part IV. Using simulants labeled with Sr^{85} or Cs^{134} f_A was obtained by extrapolation to Day + 1 of the curve for f_R versus time for the period 7 to 50 days after the simulant was swallowed. The relationship: $f_A = c \times f_R$ at 14 days, was determined. For Sr^{85}, c = 1.56; and for Cs^{134}, c = 1.13. We used the average, c = 1.35, to estimate f_A for the real fallout. The average amount of dose absorbed, 3.2 per cent (f_A x 100), was much less than we expected and even the largest value—8.8 per cent in the case of KO—was smaller than the amount customarily assumed. In two cases—JA and OR—the final counting rate for all energies was the same or less than the subject's 60 minute background count (nsc) and in these cases

Table III-3

RETENTION OF RADIOACTIVITY FROM REAL FALLOUT

Subject	Sample	First count		Last count		Decay factor	Corrected net cpm	f_R	f_A
		Day	Net cpm	Day	Net cpm				
LA	#4	+6	26,400	+20	210	6.2	1302	.049	.066
IF	#4	+7	18,860	+21	120	4.9	588	.031	.042
RE	#5	+9	26,140	+22	94	3.2	301	.012	.016
SH	#5	+6	27,700	+22	11	5.4	59	.002	.003
SA	#6	+6	31,800	+20	114	4.7	536	.017	.023
HU	#6	+6	24,350	+20	50	4.7	235	.010	.013
JA	#7	+9	38,950	+23	nsc	4.8	-	-	-
LO	#7	+6	19,960	+20	205	4.8	984	.049	.066
KO	#8	+6	29,470	+20	348	5.5	1914	.065	.088
OR	#8	+7	49,220	+21	nsc	5.0	-	-	-
							Mean:	.024	.032

we have assumed that no activity was absorbed.

On the last day of the experiment the highest counting rate for all energies was 348 net cpm for KO on D + 20. The probable error of this rate is 1.5 per cent. The lowest final count—11 net cpm for SH on D + 22—has a PE of 34 per cent. Several subjects were counted again a few weeks later, but in every case the rate was not significantly different from the background count.

Discussion

Our findings demonstrate some of the vicissitudes encountered in a study of the consequences of ingestion of week-old silicaceous local fallout. These include: (1) variations in the size and the nuclide-content of the particles; (2) rapid radioactive decay; (3) uncertain correlation between chemical solubility in vitro and biological availability as measured by the fraction of activity absorbed; (4) biological variability in the function of the human gut; and (5) the limitations of whole body counting. In spite of these difficulties and the attendant uncertainties, the information obtained provides a better basis for evaluation of the relative hazards of ingestion of local fallout than is possible by indirect methods and studies of wild animals.

When the samples were received on D + 5 we had no information about their composition: we only knew that the material was local fallout from a land-surface detonation and that the particles had been sorted into several categories of size. Standard references (such as Hunter and Ballou) allow one to make an educated guess about the relative abundance of FP at the time the samples were fed: a list of these is given in Table III-4. The complex decay pattern of FP mixtures makes analysis of the γ-ray spectrum difficult even under the most favorable circumstances. The spectra obtained with the WBS after ingestion (Figure III-1) are further complicated by mass absorption effects, Compton scattering, and uncertain geometry. Under the conditions of our study it was not feasible to analyze rigorously such spectra. Division of the output of the WBS into arbitrarily selected energy ranges was not particularly helpful, although the data in Table III-2 suggest that nuclide composition varied among the particle sizes. When the final counts are tabulated on the basis of energy range little additional information is gained (Table III-5). Range B is the only one in which there were significant counting rates for every subject. Since this range includes the principal photopeak of I^{131} it is tempting to attribute the average

Table III-4

PRINCIPAL γ-EMITTING FP IN FALLOUT

Nuclide	Energy of principal photopeak Mev	Half-life days	Fission yield per cent	Relative abundance on D + 7 per cent
Xe^{133}	0.081	5	6.5	12.0
Nd^{147}	0.092	11	2.6	4.2
Ce^{141}	0.142	33	5.7	4.8
Ba^{140}	0.162	13	6.3	9.0
I^{131}	0.284	8	2.9	6.0
Ru^{103}	0.498	40	2.9	2.0
Zr^{95}	0.722	65	6.3	2.5
Nb^{95}	0.765	35	6.3	2.5
Y^{91}	1.190	58	6.0	2.5

Source: Radiological Health Handbook.[16]

Table III-5

COUNTING RATE OF FINAL COUNT BY ENERGY RANGE

Initial	Sample	A	B	C	D	E	All[c]
LA	#4	121	37	22	30	nsc[a]	210
IF	#4	70	13	20	10	7	120
RE	#5	9	38	24	15	8	94
SH	#5	nsc	23	25	nsc	6	11
SA	#6	54	20	15	19	6	114
HU	#6	63	25	4	nsc	nsc	50
JA	#7	nsc	18	15	1	4	nsc
LO	#7	125	41	20	15	4	205
KO	#8	214	86	24	25	9	348
OR	#8	nsc	7	nsc	nsc	nsc	nsc
Background,[b]	Aver:	972	290	313	182	183	1,942

Notes: (a) nsc = counting rate the same as, or less than background.
(b) Average of the subjects' background.
(c) All values are net cpm for a 60-minute count.

of 31 net cpm to that radionuclide. If we do this we can estimate that practically all of the I^{131} that should have been in these samples of local fallout was available for absorption.*

*The amount of activity ingested was about 1.0 μc: the abundance of I^{131} between D + 7 and D + 15 is approximately 0.07. If all the I^{131} was absorbed and the fraction retained in the thyroid was 0.3, then there should have been: 1.0 x 0.07 x 0.3 = 0.021 μc (21 NC) in the gland shortly after the dose was swallowed. Assuming an effective half-life of 7 days, on the last day of the study there should have been 5 NC in the thyroid. If all the counts in range B were indeed I^{131}, and if the efficiency of the WBS was 0.005, then 31/0.005 = 6,000 dpm or about 3 NC at the time of the final count.

It appears from the data in Table III-3 that there was no correlation between availability and particle size: in each size-class there was a low value for f_R and a high one. As mentioned above we had no information about the solubility of the samples we received, although fallout collected nearby was found to have solubilities ranging from 3 to 42 per cent in HCl at pH 1.0 (see Table III-1B). It is customary to assume that the average solubility of local fallout is 10 per cent, and that biological availability is of the same order. Our findings suggest that availability, on the average, is about 3 per cent of the total γ-emitting activity. Only 4 of 10 subjects retained more than 3 per cent when measured 2 weeks after fallout was ingested, and 2 had almost none.

The interval of 2 weeks between feeding and the first examination in the WBS to assess absorption was chosen because we believed that some insoluble material might remain in the gut for as long as 10 days. The studies described in Part II were performed after these experiments with real fallout; and they indicated that retention of insoluble particles (30 to 40 microns in diameter) after the 6th or 7th day was the exception. Our experience with real fallout would have been more satisfactory had counts been made at 8, 10, 12, and 14 days instead of just at 14 days. Unfortunately we did not anticipate that the fraction retained would be as small as it was, so that we planned to obtain a series of measurements between the 14th and 28th day after feeding. For the 28th day after D + 6 the decay correction factor—using $t^{-1.2}$—was about x 25, and we expected to find counting rates during the 4th week on the order of 100 net cpm for all energies. Better data could have been obtained with larger doses, but we believed that we were obligated to limit the exposure of the lower large intestine to a maximum of 100 mrad.

Part IV: Studies with Simulated Fallout

Our experiments with simulated fallout were designed to answer the question: Does the fact that radionuclides of strontium, cesium or barium are released slowly into intestinal contents from real or simulated fallout modify their metabolic behavior during and after absorption from the gut? A corollary to this is the related question: Is it really necessary to use simulants to study the metabolism of critical nuclides from ingested fallout? There does not appear to be any good reason to ask these questions in the case of the radioisotopes of iodine since there is abundant evidence that soluble salts of iodine are absorbed rapidly from any portion of the gut. There is also good evidence that the fraction of iodine in the blood that is trapped by the thyroid gland is not influenced by the manner in which the element enters the blood. There are, however, several reasons for asking the questions about strontium, cesium and barium: First, there are many gaps in our understanding of intestinal absorption of the familiar mineral elements that are classed as essential. The situation with respect to strontium—which also surely applies to cesium and barium—was epitomized by J. F. Loutit[9] in 1961: "How strontium . . . (is) absorbed from the gut is still a matter of considerable debate, as indeed is the whole subject of intestinal absorption. What appears to be certain is that it is only the small intestine which absorbs these ions; the rate is greater in the uppermost part of this long tract, though the greater mass may be absorbed down where the flow is much slower." Later in the same lecture he speculated that "the time-course of entry of strontium into the circulation may affect its fate." And second, although we have no satisfactory data, it is reasonable to suppose that the leaching of radionuclides from silicaceous local fallout in the changing chemical environment of the gut is a relatively slow process. The same is also probably true for the rate at which the sintered oxides of distant fall-

out dissolve in intestinal contents. Lacking many facts we will not be far wrong if we assume that dilute solutions of salts of strontium, cesium and barium are immediately available for absorption after they are swallowed, while compounds formed in the intestinal contents from radionuclides leached or dissolved from particulate fallout may be somewhat less available. In these circumstances it is appropriate to wonder—as Loutit did—if the time-course of absorption does affect the fate of critical nuclides. If it can be shown that there is indeed no significant difference in the rate of elimination of strontium, cesium or barium regardless of how they gained entrance to the blood, then valid studies of metabolism can be performed using the intravenous route for administration to avoid the inevitable uncertainties associated with experiments where the tracer is given by mouth.

Materials and Methods

In accordance with the recommendations of our ad hoc advisors (see Part I) the Radiochemical Project of the Minnesota Mining and Manufacturing Company prepared two types of simulants with the following characteristics:

Local Simulant (LS) was a specially prepared microsphere fabricated from leachable glass that contained tracer amounts of Sr^{85}, Cs^{134}, or Ba^{133}. The material was manufactured so that about 10 per cent of the radioactivity could be leached from it by 0.1 N HCl at 37° C in 2 hours. The activity was approximately 50 μc/gram, and particle size was in the 30 to 40 micron range. Although not entirely carrier-free, the amount of carrier was small.

Distant Simulant (DS) was either SrO + $Sr^{85}O$, or $CsSiO_3$ + $Cs^{134}SiO_3$, or BaO + $Ba^{133}O$ calcined at about 900 to 1,000° C. The calcined mass was pulverized and particles in the 30 to 40 micron range were used. The solubility specified was from 50 to 100 per cent in 0.1 N HCl. The specific activity of the DS was about 50 μc/gram at the time of preparation. In contrast to the LS the amount of carrier was relatively large.

Soak tests were performed by adding a few milligrams of simulant to 10 ml of 0.1 N HCl or 0.1 N NaOH in test tubes. The tubes were agitated constantly in a water bath at 37° C for 2 hours. After filtration the filtrates were counted in a well-type scintillation spectrometer (Autogamma). The results are shown in Table IV-1.

Solutions of $Sr^{85}Cl_2$ and $Cs^{134}Cl_2$ were prepared from carrier-free material using water as the diluent. No effort was made to obtain a soluble salt of barium for these studies.

The range of doses administered is shown in Table II-4. The amount of radioactivity fed was a compromise: we wanted to keep the radiation dose to a minimum, and we wanted enough activity absorbed to permit reliable whole body counting for several hundred days. We assumed that biological availability paralleled solubility and that the particulate nature of the material had no influence on availability. All doses were given without regard to meals or to time of day.

Results

The γ-ray spectra of 3 subjects who had ingested one or other of the radionuclides are shown in Figure IV-1. The portions of the spectrum over which counts were summed for measurement of the whole body counting rate are indicated in each case. (See also Table I-2.)

Strontium-85. The solution of $Sr^{85}Cl_2$ was fed to 12 subjects: the average per cent of dose absorbed (f_A x 100) was 17 with a range of 8 to 34 per cent (see Table IV-2). The rate of elimination of the fraction of dose absorbed was such that the average retention after 2 weeks was

Table IV-1

AVAILABILITY OF RADIONUCLIDES FROM SIMULANTS ON THE BASIS OF SOAK TESTS

Simulant	Per cent leached or dissolved in:(a)		Average per cent absorbed by subjects (f_A x 100)
	0.1 N HCl	0.1 N NaOH	
LS-Sr^{85}(b)	6.0	8.0	12.0
DS-Sr^{85}(c)	72.0	15.0	15.0
LS-Cs^{134}	1.4	5.0	31.0
DS-Cs^{134}	38.0	12.0	82.0
LS-Ba^{133}	5.0	0.7	Nil
DS-Ba^{133}	91.0	23.0	6.0

Notes:

(a) After soaking for 2 hours at 37° C.

(b) The soak test results refer to the second batch; the per cent absorbed by subjects refers to the first batch.

(c) All results apply to the second batch. Soak tests were not performed with the first batch, the average absorption of which was 32 per cent.

52 per cent with a range of 34 to 77. At 50 days average retention decreased to 36 per cent (range: 17 to 65); after 100 days it was 26 per cent (range: 18 to 30); and after 150 days only an average of 19 per cent remained (range: 6 to 24). The trials were not all of the same duration because of factors beyond our control such as vacations, graduation, and dropping out of school. The lowest value for the final total body count in this group was 46 net cpm, not corrected for decay (subject 13-2 on D + 135). The PE of this net counting rate is 5.8 per cent.

The first batch of LS labeled with Sr^{85} was fed to 2 groups of volunteers but only the first group yielded satisfactory data. As shown in Table IV-3 an average of 16 per cent of the activity was absorbed (f_A x 100) and the range varied by a factor of 4—from 6 to 25 per cent—as was the case when the solution of $Sr^{85}Cl_2$ was fed. A second batch of LS was fed to 4 subjects but the fraction absorbed was no more than a few per cent and was very little different from that found when stable microspheres were fed (See Part III). This result was surprising because our soak tests showed that about 6 per cent of the activity was leached in 0.1 N HCl and 8 per cent in 0.1 N NaOH.

The first batch of DS was fed to 5 subjects (Table IV-3) and an average of 32 per cent of the activity was absorbed, with individual values that ranged from 21 to 47 per cent. When the second batch was fed less activity was absorbed: the average was 13 per cent. The soak tests of the second batch showed that acid solubility was 72 per cent. (The solubility of the first batch of DS was not measured but the specifications called for a solubility in this range). A statistical test*

*The test used was the Wilcoxon two-sample test[10] in which the normal variable, K, is determined from the rank order of the individual measurements of 2 samples: $K = \frac{2R \pm 1 - n(N+1)}{\sqrt{\frac{n(N+1)(N-n)}{3}}}$

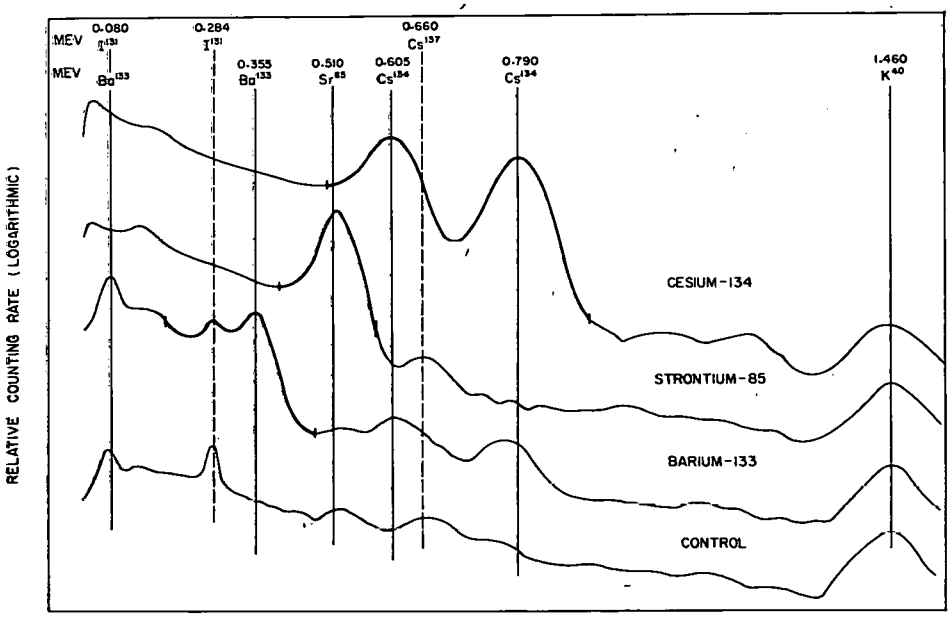

Figure IV-1. Gamma-ray spectra after ingestion of simulants. The counts for these spectra were summed for 6 Kev per channel. The heavy portion of each of the top 3 indicate the energy range over which counts were summed to measure retention. The bottom spectrum was obtained in February 1963 before the Ba^{133} simulant was fed (spectrum directly above). In addition to a small peak for Cs^{137}, there are peaks for I^{131} —presumably from concurrent tests of nuclear weapons. The two small peaks in the 3rd spectrum (Ba^{133}) at about 0.600 and 0.780 Mev are thought to be due to a trace of Cs^{134} that contaminated the BaO + $Ba^{133}O$ during manufacture. After about 100 days these peaks were no longer seen.

Table IV-2

RETENTION AFTER ORAL DOSE OF $Sr^{85}Cl_2$

Subject	Observed net cpm on D - 0	Extrapolated net cpm on D + 1	f_A	Apparent retention as per cent of f_A, on				Duration of test days	Net cpm on last day
				D + 14	D + 50	D + 100	D + 150		
13-1	12,700	2,500	0.20	44	27			77	123
13-2	13,700	2,700	0.20	54	40	18	6	135	46
13-3	11,400	1,300	0.11	77	65			76	253
13-4	13,700	4,600	0.34	59	43	29	20	135	260
19-1	31,600	3,300	0.10	67	33	30	24	151	157
19-2	30,900	4,000	0.13	50	34			75	587
19-3	33,300	9,800	0.29	41	29	25	22	153	412
19-4	32,600	4,200	0.13	43	33	30	24	149	204
20-1	22,600	1,900	0.08	34	17			61	159
20-2	21,700	4,000	0.18	47	29			61	604
20-3	18,300	2,700	0.15	54	41			58	544
Average			0.17	52	36	26	19		

where R = sum of the ranks of the smaller sample; N = total number of cases; n = number of cases in the smaller sample.

Table IV-3

RETENTION OF Sr^{85} RELEASED FROM SIMULANTS

Subject	Observed net cpm on D - 0	Extrapolated net cpm on D + 1	f_A	Apparent retention as per cent of fraction absorbed				Duration of test days	Net cpm last day
				D + 14	D + 50	D + 100	D + 150		
LS-1	19,000	4,800	0.25	30	22	21	-	199	136
LS-2	17,000	2,400	0.14	52	38	37	29	247	57
LS-3	17,000	1,800	0.11	43	29	24	21	164	95
LS-4	18,000	2,100	0.24	52	38	28	-	242	139
LS-5	12,000	700	0.06	34	19	14	-	245	14
Average:			0.16	42	29	25			
1st Batch									
DS-1	14,000	3,800	0.21	33	21	18	-	164	144
DS-2	15,200	7,200	0.47	20	9	-	-	166	150
DS-3	14,700	4,500	0.30	37	22	17	-	90	433
DS-4	16,700	4,300	0.26	31	18	13	-	168	140
DS-5	13,400	6,400	0.34	27	16	11	-	166	183
Average:			0.32	30	17	12			
2nd Batch									
DS-6	14,100	2,000	0.14	53	53	15	-	114	nsc
DS-7	13,000	1,700	0.13	71	59	54	-	145	nsc
DS-8	13,500	2,100	0.16	52	38	-	-	97	nsc
DS-9	9,500	700	0.07	67	70	-	-	53	219
Average:			0.13	61	55				

showed no significance to the difference between the average f_A for the second batch of DS, the second batch of LS, and the solution of chloride. When the results with the first batch of DS (average f_A = 0.32) were compared with all the others the difference was highly significant: P = 0.004.

After absorption of Sr^{85} from the gut the rate of elimination was evaluated on the basis of per cent retention at 14, 50, 100 and 150 days. In practice, the measured values for activity retained were plotted as net cpm corrected for decay on log-log paper. The value for f_A expressed in net cpm was entered on the ordinate for day 1. Net counting rates for days 14, 50, 100 and 150 were read off the curve and expressed as per cent of the extrapolated value for day 1. The statistical test showed no significant difference between retention of activity from the chloride solution, LS, or the second batch of DS. These data therefore were combined and plotted as open circles on Figure IV-4. The average for retention of Sr^{85} from the first batch of DS are indicated by closed circles. The range of values within the various groups was so great that any distinction between the sources was of doubtful significance. Accordingly the median value for per cent retention by all subjects receiving Sr^{85} at 14, 50, 100 and 150 days was plotted as the crosses on Figure IV-4. The line fitted by eye to these points intersects the abscissa at about 1.5 days. This is a reasonable time for absorption to be complete. The equation for this line is: $R(t) = 60t^{-0.2}$, $t \geq 1$ week. This relationship predicts that after 52 weeks, retention of Sr^{85} will

be approximately 16 per cent.

An unexpected increase or decrease in the whole body counting rate occurred at some time among the serial measurements of 16 of the 35 subjects who received Sr^{85}. Some of these are illustrated in Figure IV-2 where net counting rates corrected for decay are plotted against time in days on log-log coordinates. Initially, we supposed that these abnormal counts were caused by malfunction of the equipment and discontinued measurements of those subjects. When careful review of the operation of the WBS failed to provide an explanation for the majority of the abnormal counts the practice of terminating experiments where they occurred was stopped. The same phenomenon was observed when DS - Ba^{133} was used (see below), but there were only occasional unexpected variations of the counting rates with any of the Cs^{134} tracers, and none with any of the standard sources used to validate the performance of the instrument.

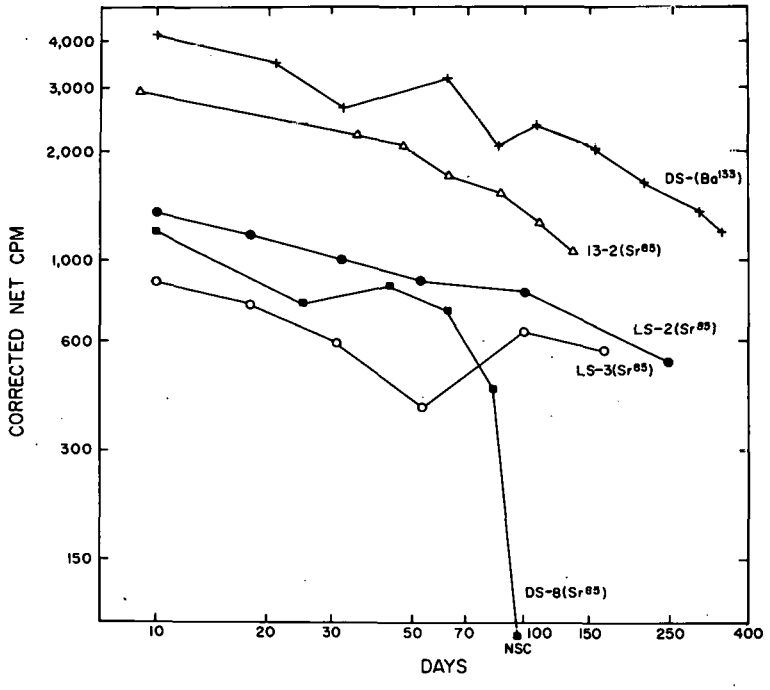

Figure IV-2. Unexpected variations after Sr^{85} and Ba^{133}. The topmost curve—DS-Ba^{133}—is subject #1, Table IV-5, who absorbed the largest amount of barium. The curve for LS-2, Table IV-3 shows what we expected to find on serial counting to measure retention of Sr^{85}. The other 3 curves demonstrate unexpected variations which—like those in the top curve—could not be attributed to malfunction of equipment or other errors.

Cesium-134. The solution of $Cs^{134}Cl_2$ was fed to 4 volunteers who absorbed (f_A x 100) 90, 90, 89 and 87 per cent, respectively. When the LS was fed, absorption was 36, 29 and 29 per cent, respectively. In our soak tests of the LS about 2 per cent of the activity was leached in 0.1 N HCl at 37° C in 2 hours, and 5 per cent in 0.1 N NaOH under the same conditions. With the DS the average absorption for 5 subjects was 82 per cent. The solubility of the sintered $Cs^{134}SiO_3$ in our soak tests was 38 per cent in acid and 12 per cent in alkali. In all of the subjects who re-

ceived Cs^{134} the rate of elimination of the fraction of dose absorbed followed a single exponential function for as long as measurements of f_R were made. Table IV-4 gives the values for f_A, and for rate of elimination expressed as the half-time in days. The mean half-time (T_b) for the 12 subjects was 91 ± 18 days. The elimination rate was not influenced by the form in which the tracer was administered: the results were the same for the solution and the particles (P = 0.40).

Table IV-4

BIOLOGICAL TURNOVER OF Cs^{134}

Subject	Tracer used	f_A	Measured half-life (days)	Half-life corrected for decay* (days) T_b	Duration of test (days)
1	Cl	0.90	63	70	207
2	Cl	0.90	77	97	43
3	Cl	0.89	110	129	173
4	Cl	0.87	96	112	107
5	DS	0.84	63	70	49
6	DS	0.83	71	80	159
7	DS	0.82	69	78	88
8	DS	0.80	92	107	159
9	DS	0.73	71	80	159
10	LS	0.36	79	90	107
11	LS	0.29	74	84	105
12	LS	0.29	81	92	105
		Mean:	79	91	
		Standard deviation:		±18	

*T_r = 840 days.

Barium-133. The local simulant labeled with Ba^{133} was fed to 3 subjects: in one case retention (f_R x 100) of approximately 1.0 per cent was found on the 10th day, but 11 days later no activity could be detected. On our soak tests 5 per cent of the activity was leached from the LS in 0.1 N HCl, and 0.7 per cent in alkali. The DS was fed to 8 subjects, 4 of whom retained more than 1.0 per cent of the dose at the 10th day. The data for these 4 are given in Table IV-5. Absorption (f_A x 100) was 15, 6, 3, and 1 per cent, respectively. Elimination was slow and at 150 days the amount retained was 42, 18 and 25 per cent, respectively. In our soak tests the solubil-

Table IV-5

RETENTION OF Ba^{133} RELEASED FROM DISTANT SIMULANT

Subject	Observed net cpm on D - 0	Extrapolated net cpm on D + 1	f_A	Apparent retention as per cent of fraction absorbed				Duration of test days	Net cpm last day
				D + 14	D + 50	D + 100	D + 150		
1	31,000	4,800	0.15	81	58	46	42	340	1,190
2	28,800	1,800	0.06	67	36	33	-	106	677
3	24,200	740	0.03	73	43	42	18	150	127
4	22,700	200	0.01	75				85	142
		Average:	0.06	74	44	40	25		

ity of the DS was 91 per cent in acid and 23 per cent in alkali. Three of the 4 subjects who received the DS displayed unexpected variations in the serial counts which were as marked as in the case of those tested with Sr^{85} (see Figure IV-2).

Dose from Internal Radiation. Estimates of the internal radiation dose received by the volunteers are given in Table II-4. The largest dose to the lower large intestine—696 mrads—occurred when the stable Cs^{134} microspheres were used to study transit time. This is about one-half of the maximum permissible internal dose to a single organ (1.2 rems in any 13-week period) according to the recommendations of ICRP for persons in Exposure Category B. The average radiation dose to the LLI from Cs^{134} was probably less than 300 mrads. The largest whole body dose was also supplied by Cs^{134} following absorption from the DS: approximately 165 mrads, using T = 70 days. This is about 1/10 of the maximum permissible internal dose recommended by ICRP for persons in Category B. The largest radiation dose to bone + bone marrow was 18 mrads from $Sr^{85}Cl_2$, using T = 65 days.

Discussion

The principal objective of these experiments was to answer the question: Does the fact that radionuclides of strontium and cesium are released slowly into intestinal contents from real or simulated fallout modify their metabolic behavior during and after absorption from the gut? As a preliminary it was necessary to feed solutions of the chloride salts to obtain baselines for comparison of the time-course of elimination of radioactivity leached or dissolved from particulate simulants. Although we have no data to support the assumption, we assumed that absorption of the solutions occurred rapidly and predominantly in the upper small intestine, while absorption of leached or dissolved activity occurred slowly from more distal portions of the gut where the in-residence time of the simulant was relatively long (see Table II-1). The null hypothesis that we tested can be stated as follows: The metabolism of strontium and cesium that enter the blood from the intestinal tract is not affected by the site at which intestinal absorption occurs nor by the rate of absorption. Our results support the null hypothesis since we found that the rate of elimination (or retention as a function of time) was not significantly different, whether the tracer was given in solution or as a particulate simulant. To evaluate the significance of such differences as were observed we used the Wilcoxon two-sample test which is based on the rank order of the results rather than their means and standard deviations. On the basis of our findings we conclude that it is not necessary to use simulants to study the behavior of FP absorbed from ingested fallout.

Although we did not administer either Sr^{85} or Cs^{134} by intravenous injection the results we obtained for rate of elimination after intestinal absorption were sufficiently similar to those reported in the literature for intravenous injection to warrant the conclusion that the parenteral route is satisfactory for most studies of the metabolism of these elements. This is an important conclusion since the parenteral route has obvious advantages over the oral, the chief of which are that the amount of activity entering the blood can be known with certainty, and that zero time is definite.

Even though our principal objective was to examine the need to use simulants to study internal deposition of FP from fallout, considerable information was obtained about 2 aspects of the metabolism of strontium, cesium and barium: intestinal absorption and retention in a small group of healthy active adults. In addition, our findings demonstrate some of the problems en-

countered when the metabolism of bone-seeking radionuclides is investigated by whole body counting. We shall consider each element in turn.

Cesium. The metabolism of cesium has been studied by many investigators: after accidents with Cs^{137}, and after parenteral and oral administration of salts of Cs^{134} and Cs^{137}.(11) The values reported for biological half-time (T_b) range from 65 to 135 days. Cesium chloride is readily absorbed, and our results (f_A = 0.90 for the chloride, and 0.82 for the oxide) are in good agreement with those reported by others. There is general agreement that a single exponential function is adequate to express the rate of elimination. In our group of 12 subjects (Table IV-4) the time for disappearance of 1/2 of the Cs^{134} absorbed ranged from 70 to 129 days with a mean of 91 and a standard deviation of ± 18 days. The extreme values (T_b = 70 and 129 days) were found in the two longest experiments: 207 and 163 days, respectively, after taking $Cs^{134}Cl_2$. Although the series is not large it affords a good estimate of the biological variability of the excretion of cesium: coefficient of variation = 0.20.

Since most of the radiocesium is in muscle and soft tissue the efficiency with which the whole body detectors can "see" it should change little—if at all—with time. In all 12 cases the time course of retention was quite regular, and only in the 2 shown in Figure IV-3 was there any unexpected deviation of the net counting rate.

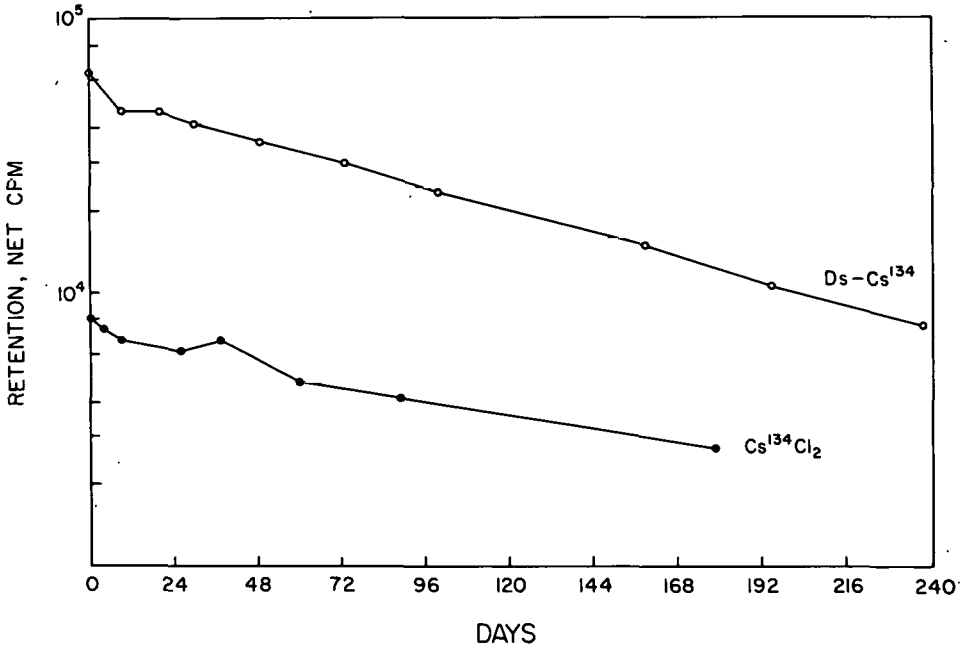

Figure IV-3. Unexpected variations after Cs^{134}. These are the only two instances among more than 60 whole body counts where the result deviated significantly from the value expected. Except for the abnormal value in each curve, elimination followed a single exponential function.

Strontium. There are many reports in the literature about the metabolism of strontium using the stable isotope as well as Sr^{85}, Sr^{87m}, Sr^{89} and Sr^{90}.(9) In ICRP Publication No. 2 (see Table I-1) the value for f_1—the fraction entering the blood from the gastrointestinal tract—is given as 0.3. In 12 of our subjects fed the solution of $Sr^{85}Cl_2$ the average fraction absorbed (f_A)

was 0.17 with a range: 0.08 to 0.34. Cohn, Spencer, Samachson and Robertson[12] reported absorption of 20.7 and 16.4 per cent, respectively, by 2 patients with osteoporosis. Spencer, et al.,[13] using Sr^{90} in contaminated food as the tracer, found a mean absorption of 15.8 ± 3.01 per cent in a group of 12 young volunteers. Loutit[9] believes that "around 20 per cent seems to be a fairly representative figure to take for absorption of soluble strontium salts." It is of interest that when he gave 100 - 200 mg of strontium as a soluble salt in water, some 35 per cent was absorbed. He attributed the larger absorption under these conditions to a mass effect. In our study, the largest value for f_A (0.47) was found in one of the subjects who received the first batch of the DS which contained abundant carrier SrO. The biological variability of absorption of strontium is thus, much greater than that for cesium. When we fed $Sr^{85}Cl_2$ absorption ranged from 8 to 34 per cent, and in the entire group of subjects the range was 6 to 47 per cent. If we set aside the 5 subjects who received the first batch of DS because their average absorption was significantly different from all the others ($P = 0.004$), then we can treat the remaining 20 as a sample that received tracer amounts of strontium. For this group, the mean absorption was 16.4 ± 7.9 per cent, and the median was 14.0 per cent. The coefficient of variation, 0.48, is greater than that reported by Spencer, et al.;[13] and is also much larger than that for cesium.

The general agreement about the extent of absorption of strontium from the gut does not extend to retention. Reports in the literature vary so greatly that it is not possible to cite a consensus. Biological half-life is often an ambiguous concept and the wide range of values reported for Sr turnover may be due in part to imprecise definition of the term. Using an exponential model Cohn, et al.[12] reported biological half-times ranging from 210 to about 1,000 days. Loutit[9] estimated that about 1/7 of a dose of strontium is due for slow turnover along with the bone in which it is incorporated. He calculated the rate of bone replacement as 6 per cent per year, so that T_b for strontium in bone would be about 10.5 years (3,800 days). This is less than the value proposed by Committee II of ICRP: T_b = 18,000 days. In general, our results are consistent with Loutit's estimate that about 1/7 of the strontium absorbed remains in the body at the end of the first year. If excretion by our subjects had continued at about the rate that we observed during the first several hundred days, then about 16 per cent of the Sr^{85} absorbed would have been retained at the end of the first year (see Figure IV-4).

We were perplexed by the occasions when the net counting rate was significantly different from that expected on the basis of previous serial measurements. After excluding all possible operating errors, unexpected results were obtained in 16 of the 45 subjects who received Sr^{85}. Examples of these are shown in Figure IV-2. The curve for LS-2 is satisfactory, while that for DS-8 demonstrates almost complete disappearance of Sr^{85} between the 62nd and the 100th day. Four others behaved in the same fashion, all occurring during the summer months. Aside from the possibility that vigorous physical activity may have been responsible we have no explanation for the occurrence. In several subjects there was an unexplained increase in the net counting rate as illustrated by the curve for LS-3. It is conceivable that redistribution of Sr^{85} in the skeleton permitted the detectors to "see" the activity with greater efficiency. This could happen if strontium deposited in the vertebrae and ribs was relocated to arms or legs where there is a smaller amount of overlying soft tissue. All subjects were counted in the prone and the supine position to compensate for unequal anterior-posterior distribution such as may occur in the trunk region. Obviously such variations complicate any study of long term retention.

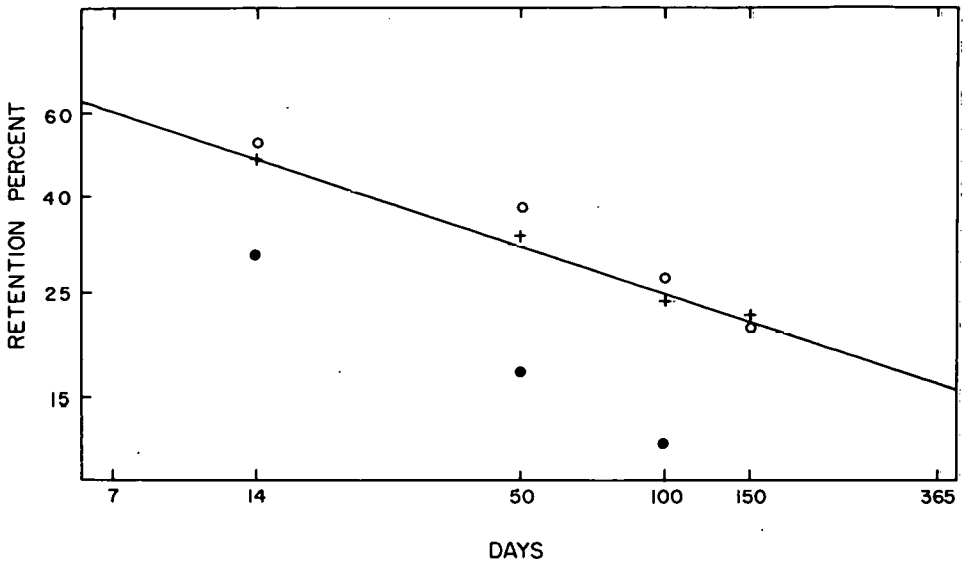

Figure IV-4. Long term retention of Sr^{85}. The open circles (o) are averages for retention by 20 subjects who received either $Sr^{85}Cl_2$, LS, or the second batch of DS. The closed circles (●) are the averages for the 5 subjects who received the first batch of DS. The median of the values for retention by all 25 subjects is indicated by the crosses (+).

Barium. Because of their cardiotoxicity little is known about the long term metabolism of barium salts beyond the fact that approximately 70 per cent of the fraction absorbed from the gut goes to bone where the half-life is reported to be 65 days (Table I-1). We fed DS consisting of BaO + $Ba^{133}O$ to 8 subjects, but only 4 absorbed a sufficient amount to permit an estimate of f_A. Long term retention could be followed in 3 of these for times ranging from 100 to 340 days. Unexpected variations of the net counting rate occurred in all 3 and resembled those seen with Sr^{85}. The data for the subject who absorbed the most barium (f_A = 0.15) are shown in Figure IV-2. The configuration of the curve resembles that for strontium, and retention measured at about 1 year (340 days) was 25 per cent of the amount absorbed. The DS made with Ba^{133} was the most soluble of the simulants used.

Part V. Conclusions

After two and a half years of work and the planned exposure of 102 healthy volunteers to small amounts of internal radiation it is appropriate to ask what we have learned that has relevance for Civil Defense:

First, we are not in much better shape than when we started with respect to our ability to predict the magnitude of the hazard from internal deposition of radioactivity following ingestion of fallout particles. It appears that local silicaeous fallout is not so soluble as it was assumed to be—if our sample was at all typical. The biological availability of radioactivity from such fallout was about 1/3 of the value usually quoted. This small advantage is offset by the uncertainty of intestinal motility which may vary over quite a wide range. There is also evidence—not too conclusive perhaps—that the intestinal contents of man are much more effective than dilute acid or alkali as a leaching agent for the glassy simulant that we used. We have not studied the reactions responsible for this and cannot say whether enzymes, chelating agents or intesti-

nal microflora are responsible. On the basis of our limited experience it does not seem proper to equate biological availability with solubility or leachability as measured by soak tests using 0.1 Normal acid and alkali.

Second, we have demonstrated that it is not necessary to use particulate simulants of fallout to study the metabolism of such critical nuclides as those of strontium, cesium or barium. The metabolic fate of strontium and cesium that gain entrance to the blood is apparently not influenced by the manner or rate at which they get there, and presumably the same is true for barium. This conclusion is not trivial, however, because it was perfectly legitimate to speculate that there might be quantitative or qualitative differences in the fashion in which the body disposes of material injected intravenously, and unknown chemical compounds of the same element absorbed from the gut.

Third, we learned quite a bit about the distribution of such values as the fraction of dose absorbed from the gut and the rate of elimination of strontium, cesium, and barium. This was possible because of the larger number of volunteers who were willing to participate in a study that concerned an aspect of Civil Defense. It was also possible because of the comparative ease of measuring long term retention of γ-emitting nuclides using the whole body counter. The important finding was a better delineation of biological variability, which is considerable for cesium, and much greater for strontium and barium. The range of variability was greater than we had anticipated.

Finally, there appears to be little difference between our findings with healthy active volunteers and the results reported by others who studied hospitalized patients whose metabolic state was not greatly disturbed by illness.

Our findings may be used to estimate probable internal dose of radiation following ingestion of typical local silicaceous fallout soon after detonation of a nuclear weapon. Any estimate of the amount of a particular critical nuclide absorbed will depend on the assumptions made. The examples that follow are based on one set of assumptions:

(i) A radiation dose to the mucosa of the lower large intestine greater than about 100 rads during, say, 1 week will cause diarrhea and result in decreased absorption.

(ii) Following Dunning,[8] ingestion of 5 mc of 1-day old fallout will deliver a dose of about 100 rads (48 μc = 1 rad).

(iii) The availability for absorption of critical nuclides is equal to relative abundance time 0.03—our average value for f_A. The exception is I^{131} where availability equals relative abundance.

- For I^{131} deposited in the thyroid gland:
  $1 \times 0.06 \times 0.3 = 0.018 \times 5{,}000 = 90$ μc.
- For long term retention of Sr^{90} beginning 1 week after ingestion:
  $0.03 \times 0.05 \times 0.14 \times 0.6 = 0.000126 \times 5{,}000 = 0.63$ μc.
- For Ba^{140} deposited in bone during ingestion:
  $0.03 \times 0.09 \times 0.06 \times 0.7 = 0.0001134 \times 5{,}000 = 0.57$ μc.
- For Cs^{137} in muscle and soft tissue:
  $0.03 \times 0.01 \times 0.9 = 0.00027 \times 5{,}000 = 1.35$ μc.

Internal radiation dose can then be calculated using the biological and physical constants listed in the ICRP publication, or the biological constants reported in this study.

Summary

1. The behavior of real and simulated fallout following ingestion was studied in 102 volunteers using the whole body gamma spectrometer.

2. Ten volunteers ingested samples of typical local fallout. The average biological availability of the radioactivity in this material was 3 per cent. Two of the subjects absorbed almost none, and only 4 of the 10 absorbed more than 3 per cent.

3. The rate of excretion of insoluble particulate material from the gastrointestinal tract was followed in 27 subjects. On the average about 1/2 the material was excreted during the first 2 days following ingestion. In all but 3 of 17 subjects 99.9+ per cent was gone by the 7th day.

4. Simulants of fallout labeled with Sr^{85}, Cs^{134}, or Ba^{133} were fed to 43 subjects, and solutions of $Sr^{85}Cl_2$ or $Cs^{134}Cl_2$ were fed to 22. The rate of elimination of strontium and cesium was the same whether the tracer was given in solution or whether it was absorbed from the simulant.

5. On the average, about 16 per cent of the strontium tracer was absorbed from the gut. Of the amount absorbed, about 60 per cent was retained at the end of the 1st week and about 16 per cent at the end of 1 year. Carrier strontium enhanced absorption but appeared to decrease retention to some extent. The biological variability of absorption of strontium was large: when $Sr^{85}Cl_2$ was fed the fraction absorbed ranged from 0.08 to 0.34.

6. In 12 subjects the biological half-time for elimination of Cs^{134} was 91 ± 18 days. When $Cs^{134}Cl_2$ was fed about 90 per cent of the tracer was absorbed.

7. Using BaO + $Ba^{133}O$ as a distant simulant (DS) average absorption was 6 per cent in 8 subjects, with a range of 1 to 15 per cent. Elimination of barium by one subject was slower than for strontium: 25 per cent of the amount absorbed was retained at the end of 1 year.

8. There was no correlation between the biological availability of the simulants and leachability or solubility as measured by soak tests in 0.1 N HCl and 0.1 N NaOH.

Acknowledgments

The authors are indebted to Dr. Carol M. Newton for assistance in the early phase of this study. They are especially grateful to the 102 volunteers who hoped that they were making a contribution to Civil Defense.

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